

The Obstacle Avoidance Path Planning of Six Degrees of Freedom

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Abstract: In the rapidly advancing field of robotics, motion planning and control of robotic arms have emerged as critical research areas, driven by their widespread applications in manufacturing, healthcare, and automation. This paper focuses on single and six-degree-of-freedom (DOF) robotic arm systems, implementing a motion control method based on S-type velocity planning. S-type planning divides the arm's motion into three distinct phases: acceleration, uniform velocity, and deceleration. This approach ensures smooth transitions between phases, avoids abrupt acceleration changes, and significantly reduces vibrations and mechanical impacts, thereby enhancing the system's overall performance and longevity. The paper derives the mathematical model of S-type planning, providing a detailed analysis of velocity, acceleration, and jerk curves. Experimental results demonstrate its effectiveness in improving motion stability for single-DOF arms, showcasing its ability to deliver precise and reliable control. For more complex six-DOF systems, an innovative joint velocity coordination algorithm is introduced. This algorithm addresses the inherent joint coupling challenges, ensuring overall motion coordination and improving the trajectory accuracy of the end-effector. Rigorous simulation experiments validate the method's superiority in enhancing stability, minimizing vibrations, and maintaining high precision in multi-DOF systems. In conclusion, this research provides robust theoretical foundations and practical insights for multi-DOF robotic arm motion planning. The proposed S-type velocity planning method and joint coordination algorithm offer significant potential for real-world engineering applications, paving the way for further advancements in robotics technology. These contributions are expected to play a pivotal role in optimizing robotic systems for diverse industrial and scientific applications.

Keywords: S-Type Velocity Planning, Six-DOF Systems, Robotics Technology

1. Introduction

As robotics technology permeates industries like manufacturing, healthcare, and services, motion planning and control of robotic arms have become a core research focus [1-2]. Effective motion planning must ensure precise path positioning, smooth movement, task efficiency, and mechanical protection, making a scientifically sound algorithm crucial for enhancing robotic arm performance. For multi-degree-of-freedom (DOF) systems, such as six-DOF robotic arms, the complexity increases exponentially. These systems require precise coordination of multiple joints to achieve accurate end-effector operation in complex workspaces[3]. Motion planning must account for kinematic and dynamic constraints, as well as smooth transitions in joint speed and acceleration, to

minimize vibrations, shocks, and potential structural damage^[4]. Achieving smooth and efficient motion planning in multi-DOF systems remains a key challenge in robotics research.

S-type velocity planning has emerged as a popular strategy due to its unique advantages. By dividing motion into acceleration, uniform, and deceleration phases, it reduces abrupt acceleration changes, ensures smooth transitions, and minimizes system vibrations and impacts. In single-DOF systems, S-type planning has proven [5-6] effective in enhancing stability and reliability. However, applying it to six-DOF systems introduces significant challenges, as each joint requires independent speed planning while accounting for complex joint coupling to ensure overall coordination and stability.

This paper explores S-type velocity planning for single and six-DOF robotic arm systems. For single-DOF systems, it derives the mathematical model of S-type planning, analyzes velocity, acceleration, and jerk curves, and validates its effectiveness in improving motion stability through experiments. For six-DOF systems, the study innovatively extends S-type planning [7] by proposing a joint velocity coordination algorithm tailored for multi-DOF systems. This algorithm optimizes joint coordination and ensures end-effector trajectory accuracy. The research provides a robust theoretical foundation and practical solution for multi-DOF motion planning, offering significant potential for real-world engineering applications and advancing robotics technology [8].

2. Kinematic analysis of the S-type curves

In the multi-degree-of-freedom robotic arm motion control, in order to smooth the movement of the mechanical arm, that is, the acceleration will not change, the S-shaped curve is used to finely regulate the acceleration to ensure the smooth movement of the robotic arm and avoid the acceleration mutation. The following is a detailed analysis of the seven stages of the S-shaped curve in the multi-degree of freedom robotic arm motion:

2.1. Plus acceleration stage

In the multi-degree of freedom robotic arm motion planning, the first stage of the S-shaped 0curve is the acceleration stage. The acceleration gradually increases from the beginning, and the change rate of speed keeps rising, which helps the mechanical arm to overcome the static inertia smoothly and start slowly.

For the acceleration phase, assuming 0that the time from the T_1 beginning is experienced j and the acceleration is, the corresponding acceleration, velocity and displacement are respectively:

Since, $a_0 = 0$ so the acceleration expression is

$$a(t) = jt \quad (1)$$

The velocity $v(t)$ is $a(t)$ the integration t of the acceleration on the time, and the formula is:

$$v(t) = \int_0^t a(t) dt = \frac{1}{2}jt^2 + v_0 \quad (2)$$

And because $v_0 = 0$, so the speed expression is

$$v(t) = \frac{1}{2}jt^2 \quad (3)$$

Displacement $s(t)$ is $v(t)$ velocity t to the integral of time, the formula is:

$$s(t) = \int_0^t v(t) dt = \frac{1}{6}jt^3 + s_0 \quad (4)$$

Since, $s_0 = 0$ the displacement expression is:

$$s(t) = \frac{1}{6}jt^3 \quad (5)$$

2.2. The uniform acceleration phase

In multi-degree-of-freedom robotic arm motion planning, the uniform acceleration stage of the S-shaped curve is crucial for connecting the acceleration and deceleration phases. Following the acceleration stage, it ensures steady speed growth, smooth movement, and avoids abrupt acceleration changes. At its start, the speed seamlessly matches the acceleration stage's final speed, while acceleration transitions from variable to constant, maintaining motion continuity and preventing speed or acceleration discontinuities.

The acceleration during this period remains unchanged, equal T_1 to the immediate acceleration at the end of the acceleration phase of

$$a(t) = a(T_1) = jT_1 \quad (6)$$

The velocity increases linearly over time. Due to the constant acceleration, the speed increment is fixed per unit time. The formula is:

$$v(t) = v(T_1) + a(t)(t - T_1) \quad (7)$$

By the $v(T_1) = \frac{1}{2}jT_1^2$ formula $a(t) = jT_1$, the speed is:

$$v(t) = \frac{1}{2}jT_1^2 + jT_1(t - T_1) \quad (8)$$

The displacement grows over time as a quadratic function. Due to the increasing speed, the movement distance becomes longer in the same time interval. The formula is

$$s(t) = v(T_1)(t - T_1) + \frac{1}{2}a(t)(t - T_1)^2 + s(T_1) \quad (9)$$

2.3. Reduction acceleration stage

In the multi-degree-of-freedom robotic arm motion planning, the third stage of the S-shaped curve is the minus acceleration stage, which is to reduce the manipulator acceleration smoothly and avoid mutation.

Acceleration $-j$ is the rate of change of acceleration over time. According $a(t)$ to the $-j$ definition t of integral, acceleration is the integral of acceleration on time. The formula is:

$$a(t) = \int_{T_1+T_2}^t -j dt = -j(t - T_1 - T_2) + a_{\max} \quad (10)$$

The velocity $v(t)$ is $a(t)$ the integration t of the acceleration on the time, and the formula is:

$$v(t) = \int_{T_1+T_2}^t a(t) dt = jT_1(t - T_1 - T_2) - \frac{1}{2}j(t - T_1 - T_2)^2 + v(T_1 + T_2) \quad (11)$$

Substituting $v(T_1 + T_2) = \frac{1}{2}jT_1^2 + jT_1T_2$ it into the formula yields a speed of

$$v(t) = jT_1(t - T_1 - T_2) - \frac{1}{2}j(t - T_1 - T_2)^2 + \frac{1}{2}jT_1^2 + jT_1T_2 \quad (12)$$

The placement $s(t)$ is $v(t)$ the t integration of speed over time with the formula:

$s(t) = \int_{T_1+T_2}^t v(t) dt = \int_{T_1+T_2}^t [jT_1(t - T_1 - T_2) - \frac{1}{2}j(t - T_1 - T_2)^2 + \frac{1}{2}jT_1^2 + jT_1T_2] dt + s(T_1 + T_2)$ Because the acceleration T_1 stage and the T_3 deacceleration $T_1 = T_3$ stage are equal, so

$$s(T_1 + T_2 + T_3) = jT_1^3 + \frac{3}{2}jT_1^2T_2 + \frac{1}{2}jT_1T_2^2 \quad (13)$$

2.4. The uniform stage

In multi-degree-of-freedom robotic arm motion planning, the fourth stage of the S-shaped curve is a uniform stage, which aims to accumulate displacement at a steady speed. At the same time, maintain a high speed to improve the efficiency, with zero acceleration to reduce the change of inertia force, to achieve stable operation, to ensure high precision movement.

For the constant speed stage $T_1 + T_2 + T_3$, the time is from the beginning T_4 , and the experience time of this stage is, so the corresponding acceleration, speed and displacement are respectively:

The speed remains constant as the target speed reached at the end of the acceleration phase. The speed at this time is

$$v(t) = v_{max} \quad (14)$$

The displacement and time are linear, namely the product of displacement = constant velocity and time. The displacement at this time is

$$s(t) = v(t)(t - T_1 - T_2 - T_3) + s(T_1 + T_2 + T_3) \quad (15)$$

At the end of the fourth time period, the displacement is

$$s(T_1 + T_2 + T_3 + T_4) = jT_1T_2T_4 + jT_1^2T_4 + jT_1^3 + \frac{3}{2}jT_1^2T_2 + \frac{1}{2}jT_1T_2^2 \quad (16)$$

2.5. Add deceleration stage

In the multi-degree-of-freedom mechanical arm motion planning, the fifth stage of the S-shaped curve is the acceleration and deceleration stage, which is used as the transition stage from uniform speed to deceleration. By gradually increasing the reverse acceleration, the mechanical arm speed is steadily reduced, so as to prepare for the subsequent uniform deceleration stage.

For the acceleration and deceleration $T_1 + T_2 + T_3 + T_4$ phase, the time is from T_5 the beginning— j . The time experienced in this phase is, and the acceleration is, so the corresponding acceleration, speed and displacement are respectively:

Because the acceleration T_1 stage and T_5 the deceleration $T_1 = T_5$ stage are equal namely, so

$$a_{123451min} \quad (17)$$

$$v(T_1 + T_2 + T_3 + T_4 + T_5) = \frac{1}{2}jT_1^2 + jT_1T_2 \quad (18)$$

$$s(T_1 + T_2 + T_3 + T_4 + T_5) = \frac{11}{6}jT_1^3 + jT_1T_2T_4 + jT_1^2T_4 + \frac{5}{2}jT_1^2T_2 + \frac{1}{2}jT_1T_2^2 \quad (19)$$

2.6. The uniform deceleration stage

In the motion planning of the multi-DOF arm, the sixth stage of the S-shaped curve is the uniform deceleration stage, which steadily reduces the speed of the previous stage with constant deceleration, so as to prepare for the precise stop of the arm or the subsequent fine adjustment. At this stage, ensure the speed smooth transition, reduce the impact, improve the motion control accuracy, and ensure the stable operation of the mechanical arm.

For the acceleration and deceleration $T_1 + T_2 + T_3 + T_4 + T_5$ phase, the time is from T_6 the beginning, and the time of this phase is, so the corresponding acceleration, speed and displacement are respectively:

The acceleration during this period remains unchanged, $T_1 + T_2 + T_3 + T_4 + T_5$ equal to the immediate acceleration at the end of the acceleration phase of

$$a(t) = a(T_1 + T_2 + T_3 + T_4 + T_5) = -jT_1 \quad (20)$$

$$v(T_1 + T_2 + T_3 + T_4 + T_5 + T_6) = \frac{1}{2}jT_1^2 \quad (21)$$

$$s(T_1 + T_2 + T_3 + T_4 + T_5 + T_6) = \frac{11}{6}jT_1^3 + 3jT_1^2T_2 + jT_1T_2T_4 + jT_1^2T_4 + jT_1T_2^2 \quad (22)$$

2.7. Reduced deceleration stage

In the multi-degree-of-freedom robotic arm motion planning, the seventh stage of the S-shaped curve is the deceleration stage, which aims to allow the robotic arm to smoothly end the current motion. By gradually reducing the acceleration, the speed is smooth to the target value (often zero), avoid the mutation of speed and acceleration, reduce the mechanical stress and vibration, ensure the running accuracy and stability of the mechanical arm, and prevent the damage to the end actuator and workpiece.

For the decrement phase, assuming $T_1 + T_2 + T_3 + T_4 + T_5 + T_6$ the time from the beginning T_7 , the time j and the acceleration is, then the corresponding acceleration, velocity and displacement are respectively

The acceleration starts a_{min} at the minimum and gradually j increases at a constant acceleration, and eventually j approaches to zero at the end of this phase. Acceleration $a(t)$ is j the rate of change of acceleration over time. According to the definition of integral, acceleration is the integral of acceleration on time. The formula is:

$$a(t) = \int_{T_1+T_2+T_3+T_4+T_5+T_6}^t j dt = j(t - T_1 - T_2 - T_3 - T_4 - T_5 - T_6) + a_{min} \quad (23)$$

Because the acceleration T_1 stage and T_7 the deceleration $T_1 = T_7$ stage are equal namely, so

$$a(T_1 + T_2 + T_3 + T_4 + T_5 + T_6 + T_7) = 0 \quad (24)$$

$$v(t) = \frac{1}{2}jT_1^2 - jT_1^2 + \frac{1}{2}jT_1^2 = 0 \quad (25)$$

$$s(t) = 2jT_1^3 + 3jT_1^2T_2 + jT_1T_2T_4 + jT_1^2T_4 + jT_1T_2^2 \quad (26)$$

3. Simulation experiment

The simulation experiment of S-type speed planning method is conducted from the two sets of single degrees of freedom and multiple degrees of freedom.

3.1. Single-degree-of-freedom

For the single degree of freedom of the mechanical arm, mainly from the single degree of freedom of 0 and the single degree of freedom is not 0. For the single degree of freedom, when the initial angle is 0, its motion start position is clear, which is easy to control and plan, and is often used for simple tasks that require accurate starting state. When the initial Angle is not 0, the mechanical arm can work at a specific starting attitude, which can flexibly adapt to complex working conditions. By accurately setting the non-zero initial Angle, its working scope and application scenarios are expanded.

As shown in Figure 1, in the simulation experiment of the single degree of freedom node, the key parameters are carefully set. The initial position was exactly set to 0, while the termination position of the node was determined as 160, which clarified the start and end range for the experiment. At the same time, the maximum speed of the node is 80 and the maximum acceleration is 80 to simulate the speed and acceleration in the actual operation. A total displacement reached 4 throughout the experiment. After these basic parameters were set, after a series of careful

adjustments, the parameter combination was constantly optimized, and the simulation was finally successfully realized. The results of the simulation experiments are as follows, which will provide an important basis for further research.

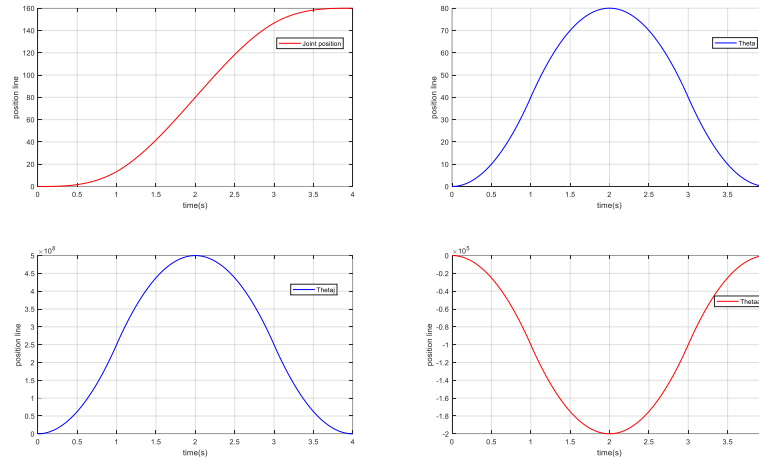


Figure 1: Single degree of freedom joint displacement, velocity, acceleration, acceleration image

In Figure 2, the initial position is accurately set to 20, while the termination position of the node is determined to be 180, which defines the range of the start and end of the experiment. At the same time, the maximum speed of the node is 80 and the maximum acceleration is 80 to simulate the speed and acceleration in the actual operation. A total displacement reached 4 throughout the experiment. After these basic parameters are set, after a series of careful adjustments, the parameter combination is constantly optimized, and the simulation was finally successfully realized. The results of the simulation experiments are as follows, which will provide an important basis for further research.

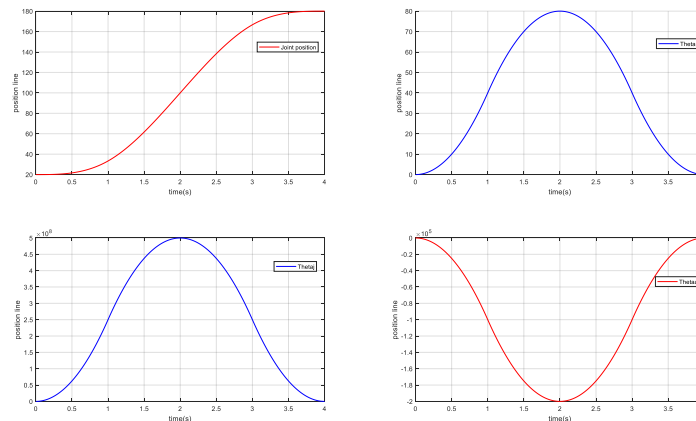


Figure 2: Single degree of freedom joint displacement, velocity, acceleration, acceleration image

In the motion control of a single degree of freedom manipulator, the research based on S-type velocity planning shows that this method has significant advantages in improving motion smoothness, reducing mechanical vibration and optimizing motion time. S-type velocity planning significantly improves the smoothness of a robotic arm's motion by introducing successive changes in acceleration and Jerk. Compared with the traditional trapezoidal speed planning, the S-type speed

planning avoids abrupt acceleration and reduces the impact of the robot arm when starting, stopping and steering, thereby reducing mechanical vibration and wear. Because the acceleration is limited by the S-type velocity planning, the vibration of the manipulator during motion is significantly reduced. This is especially important for high-precision operations (such as precision assembly or machining), which can effectively improve the positioning accuracy and operational stability of the robot arm. S-type velocity planning is not only suitable for single-degree-of-freedom robotic arms, but also can be extended to multi-degree-of-freedom robotic arms and complex trajectory planning. Its smoothness and high efficiency make it widely used in industrial robots, service robots and medical robots. In summary, the motion control method of single-DOF manipulator based on S-type velocity planning has excellent performance in motion smoothness, time optimization and vibration suppression, and has high practical value and popularization significance. Future studies can further explore its application in multi-degree-of-freedom systems and complex tasks, and improve its performance with intelligent optimization algorithms.

3.2. Six degree of freedom

As shown in Figure 3, in the study of the 6-DOF robotic arm, in order to accurately explore its motion law, an accurate model is set up. During model construction, the initial positions of all six degrees of freedom were rigorously set to 0 to ensure the consistency of the starting state. After repeated consideration, the end point position was determined to be 100,80,120,85,80 and 80, respectively, which clearly defined the target scope of the movement. The maximum speed is set to 120, and the maximum acceleration is set to 100, so as to strictly limit the movement state. After it is clear that the displacement of each degree of freedom is 4, detailed simulation experiments are carried out to comprehensively analyze the key elements such as speed, acceleration and displacement, so as to provide data support for the subsequent optimization

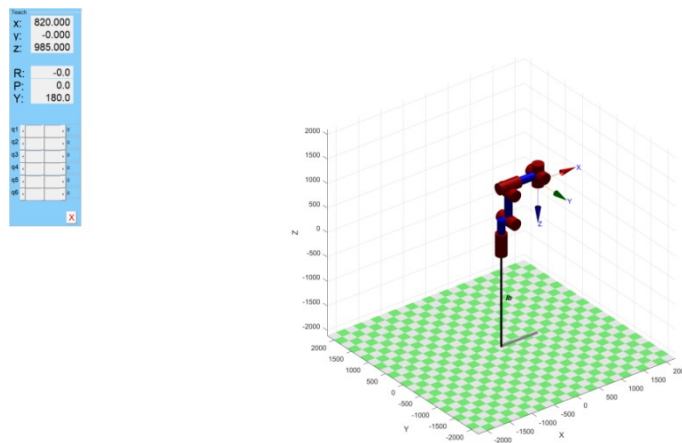


Figure 3: Simulation model of six degrees of freedom manipulator

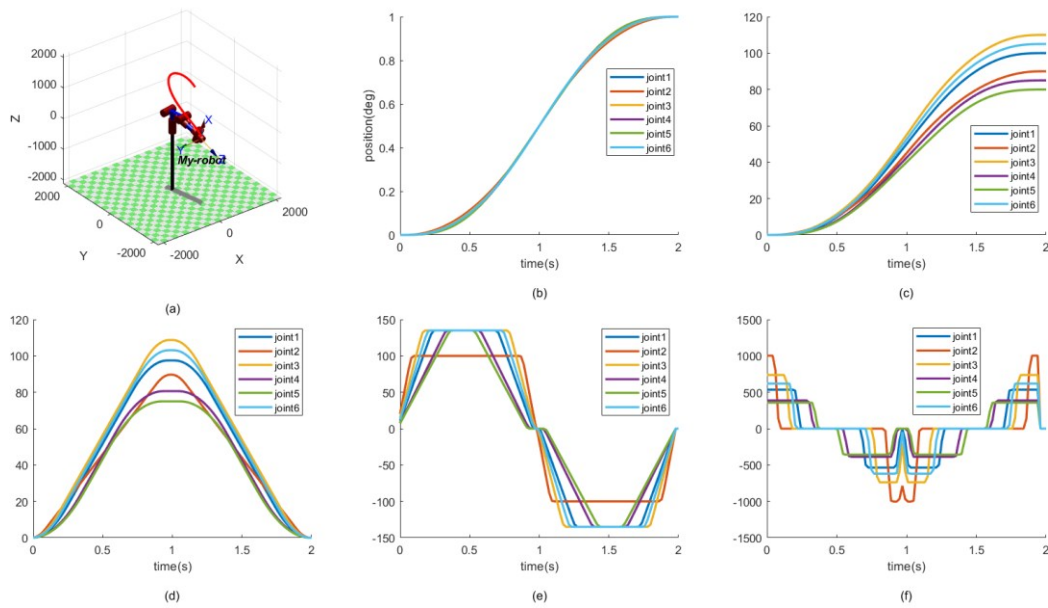


Figure 4(a) Simulation trajectory of six degrees of freedom manipulator, Figure 4(b) Normalized curve of six degrees of freedom manipulator joint, Figure 4(c) Joint position curve of six degrees of freedom manipulator arm, Figure 4(d) Velocity curve of six degrees of freedom manipulator, Figure 4(e) Acceleration position curve of six degrees of freedom manipulator, Figure 4(f) Position curve of six degrees of freedom manipulator with acceleration

The simulation results are shown in Figure 4. In the motion control of the six-DOF robotic arm, the research based on S-type velocity planning shows that this method has significant advantages in improving the smoothness of motion, optimizing the motion time and reducing mechanical vibration. The following conclusions can be drawn: By introducing the continuous change of acceleration and Jerk, S-type velocity planning effectively avoids the problem of sudden acceleration in traditional trapezoidal velocity planning. In the complex motion trajectory of the six-degree-of-freedom manipulator, the S-type velocity planning significantly improves the smoothness of the motion of each joint and reduces the impact of the manipulator during starting, stopping and steering, thereby reducing mechanical vibration and structural wear. The vibration of the 6-DOF manipulator can be effectively suppressed because the acceleration is limited by S-type velocity planning. This is particularly important for high-precision operations (such as precision assembly, welding or engraving), which can significantly improve the positioning accuracy and operational stability of the robot arm and reduce errors due to vibration. In a 6-DOF manipulator, S-type velocity planning can coordinate the motion of each joint to avoid the discontinuity of the whole motion caused by a single joint motion mutation. Through global optimization, S-type velocity planning achieves smooth transition of multi-joint motion and improves the overall motion performance of the manipulator. The parameters of S-type speed planning, such as maximum speed, maximum acceleration, and maximum acceleration, can be flexibly adjusted according to specific task requirements to adapt to different motion scenarios and load conditions. For example, in high-speed motion scenarios, efficiency can be improved by increasing the maximum acceleration; In high-precision scenarios, vibration can be further suppressed by reducing the maximum acceleration. Despite the high computational complexity of S-type velocity planning in 6-DOF robotic arms, it is fully controllable within the computational power of modern controllers. Through

the optimization algorithm and parallel computation, the computational overhead can be further reduced to meet the needs of real-time control. S-type velocity planning is not only suitable for six-degree-of-freedom robotic arms, but also can be extended to more degree-of-freedom robotic arms and complex trajectory planning. Its smoothness, high efficiency and vibration suppression ability make it widely used in industrial robots, service robots, medical robots and aerospace and other fields.

In summary, the motion control method of 6-DOF manipulator based on S-type velocity planning has excellent performance in motion smoothness, time optimization and vibration suppression, and has high practical value and popularization significance. Future studies can further explore its application in multi-degree-of-freedom systems, complex tasks and dynamic environments, and improve its performance and adaptability by combining intelligent optimization algorithms and machine learning techniques.

4. Conclusion

In this paper, we study and implement the motion control method based on S-type velocity planning for single-and six-degree robotic arm systems. The theoretical analysis and simulation experiments demonstrate the effectiveness of the proposed speed planning method in motion smoothness, trajectory accuracy and system shock suppression.

For the single DOF mechanical arm, the S-type velocity program significantly reduces the acceleration mutation in the beginning and end stages of motion, thus effectively inhibiting the vibration and shock of the system. The derivation and simulation results of the mathematical model show that the S-type planning has better motion stability than the traditional trapezoidal planning and can provide better solutions for motion control in practical applications.

In the six-degree-of-freedom robotic arm system, the proposed joint speed coordination planning algorithm not only performs independent speed planning for each joint, but also considers the coupling relationship between joints. The simulation results show that the method can ensure the trajectory accuracy of the mechanical arm end effector and realize the smooth transition of each joint movement, which significantly reduces the shock and vibration of the system in the acceleration and deceleration stages.

Overall, the study in this paper shows that S-type velocity planning methods have significant advantages in both single-and six-DOF robotic arm systems, which can effectively improve the stationarity of motion and the dynamic performance of the system. Future work will further explore the application of this method to higher degrees of freedom robotic arms as well as real physical systems, and consider introducing more constraints to optimize the planning effect.

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